DEVELOPMENT OF A DISTRIBUTED WATERSHED WATER QUALITY MODEL

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Abstract

A primary water quality problem caused by Non-Point Source Pollution (NPSP) is eutrophication, excess nutrients in receiving water bodies. The control of nutrients arising form NPSP is difficult because the source areas can be hard to identify and typical treatment methods are infeasible due to the distributed nature of the pollutants. It may be possible to reduce nutrient related water quality problems through the restoration of highly disturbed watersheds with best management practices (BMPs). While restoration attempts may provide significant returns, they can be costly to implement and often are met with resistance in agricultural communities. In order to quantify potential benefits, detailed hydrologic/water quality modeling of watersheds and the effects of BMPs is required. Extending model results beyond the range of calibration to model future conditions, such as for restoration scenarios, requires the use of physically based models that include the important processes that generate stream flow and material transport, uptake, loss, transformation, and recycling of nutrients/material. The research and development objectives of the Engineer Research and Development Center (ERDC) are to develop a watershed assessment and management model to simulate nutrients and associated material (nitrogen, phosphorus, sediment, and organic matter) transport, uptake, loss, transformation, and recycling. The model will be formulated so that it can be extended beyond the range of calibration, making it useful for analysis of future scenarios such as restoration efforts and implementation of BMPs. This paper will discuss current efforts at the ERDC's Environmental Laboratory to develop a state-of-the-art watershed water quality model.

INTRODUCTION

The concept of watershed planning is not new to the U.S. Army Corps of Engineers. Throughout its history, the Corps has incorporated watershed planning into the process by which it manages water resource systems. Even the Corps geographic organization, along watershed boundaries rather than State and county lines in most cases, supports the historic understanding of the need to manage water within a watershed context. However, this understanding and organizational concept alone are not sufficient to ensure proper protection and responsible development of the Nation's water resources in the future.

In the summer and fall of 2000, the Corps of Engineers held a series of 16 "listening sessions" around the Nation to hear what Americans thought were the major water challenges for the 21st Century. The participants provided valuable input for Federal involvement that would best help various levels of government face these challenges. One of the frequently raised topics was the need to address water challenges from a watershed view, highlighting collaboration and integration. Some present day watershed management efforts, such as the Comprehensive Everglades Restoration Plan, already promote active participation of all interested parties in the planning and decision making process. The Corps believes that this concept of integration is the key to reforming America's water development, protection, and restoration. In its recently released *Watershed Perspective for the Civil Works Program*, the Corps describes the foundation for watershed activities and involvement. The nine Watershed Principles outlined there provide the approach the Corps seeks to follow in its water resource management are: 1) Seeking sustainable water resources management; 2) Integrating water and related land management; 3) Considering future water demands; 4) Coordinating planning and management; 5) Promoting cooperation among government agencies at all levels; 6) Encouraging public participation; 7) Evaluating monetary and non-monetary tradeoffs; 8) Establishing interdisciplinary teams; and 9) Applying adaptive management as changing conditions or objectives warrant.

Unlike the single purpose, project driven initiatives that the Corps has been directed to accomplish in the past, the perspective of this new watershed approach is based on multi-purpose, multi-objective management, examining all water needs in the watershed and receiving waterbodies. With this broader context, watershed partners would collaborate to simultaneously address multiple objectives - environmental quality, social effects, and national and regional economic development.

In support of the Corps watershed approach, the System Wide Water Resources Program (SWWRP) was designed to assemble and integrate the diverse components of water resources management. Products from this program are designed to help users surpass individual project level analysis, and apply current and improved technologies for multi-disciplinary system-wide assessments. The ultimate goal, of SWWRP, is to provide the Corps, its partners, and stakeholders, the overall technological framework and analytical tools to restore and manage water resources and balance human development activities with natural system requirements.

This paper will describe the overland and channel methodologies within the Gridded Surface Subsurface Hydrologic Analysis (*GSSHA*) model, the current state of the system-wide nutrient sub-modules (SWWRP-NSM), future soil nutrient processes, future plant growth processes, and a case study of nutrient transport on the Eight Mile Run Watershed located near Eau Galle, WI. As research continues, it is anticipated that improved process descriptions will be developed and as such will be integrated into the SWWRP-NSM.

MODEL METHODOLOGY

This section will discuss the flow and sediment methodologies found within *GSSHA*, the current overland and channel nutrient process descriptions found within the SWWRP-NSM, and the proposed soil and plant growth processes.

GSSHA

GSSHA is a multi-dimensional physically based distributed watershed model that encompasses the full hydrologic cycle. The processes related to the overland and channel regimes are: 1) Precipitation Distribution; 2) Interception; 3) Infiltration; 4) Evaporation and Evapotranspiration; 5) Overland Flow; 6) Channel Flow; 7) Overland Erosion; and 8) Channel Sediment Routing.

Rainfall is always a required input within any hydrologic model. Rainfall may be input as spatially and temporally uniform, at a specified rate for a specified duration, for a single event, or rainfall may be input as spatially and temporally varying for any number of rainfall events. The rainfall interpolation techniques available for spatially varied rainfall is: 1) Inverse Distance Squared Method; or 2) Thiessen Polygon Method. NEXRAD precipitation estimates can be used in *GSSHA*, by formatting the data into a *GSSHA* precipitation file using the RADAR precipitation type card. When using NEXRAD rainfall estimates, *GSSHA* assigns a rain gauge at the center of each radar data pixel. When combined with Thiessen polygon rainfall interpolation, this reproduces the original radar pixels.

The interception of rainfall by the vegetation is modeled in *GSSHA* using the two parameter method published by Gray (1970). An initial quantity of rainfall (mm), entirely intercepted by foliage and a storage capacity are specified within the model for each landuse type.

The evaporation and evapo-transpiration models incorporated in *GSSHA* allow calculation of the loss of soil water to the atmosphere, improving the determination of soil moistures. Two different evapo-transpiration options are included: 1) bare-ground evaporation from the land-surface using the formulation suggested by Deardorff (1978); and 2) evapo-transpiration from a vegetated land-surface utilizing the Penman-Monteith equation.

Water ponded on overland flow plane cells will infiltrate into the soil as conditions permit. Infiltration is dependent upon soil hydraulic properties and antecedent moisture conditions, which may be affected by previous rainfall, run on, ET, and the location of the water table. In *GSSHA*, the unsaturated zone that controls infiltration may be simulated with a 1-D formulation of Richards' equation (RE), which simulates infiltration, ET, and soil moisture movement in an integrated fashion. Infiltration may also be simulated using traditional Hortonian Green and Ampt (GA) approaches which are simplifications of RE. There are three optional GA based methods to calculate infiltration for Hortonian basins: 1) traditional GA infiltration, 2) multi-layer GA, and 3) Green & Ampt infiltration with redistribution (GAR). The traditional GA and multi-layer GA approaches are used for single event rainfall when there are no significant periods of rainfall hiatus. The GAR approach is used when there are significant breaks in the rainfall, or for continuous simulations.

Overland flow in *GSSHA* employs the diffusive wave approximation in two dimensions (x and y). Flow is routed in two orthogonal directions in each grid cell during each time step. The watershed boundary represents a no flow boundary for the overland flow routing and when a grid cell lies on the watershed boundary, flow is not routed across the boundary. Inter-cell fluxes in the x and y directions, p and q, respectively, are computed in cell ij from the depth, d_{ij}, at the n^{th} time level using the Manning equation for the head discharge relationship in the x and y directions. Once water enters a "channel" grid cell, then the volume of water is added to the channel system and routed to the watershed outlet. The overland flow routine does allow for depression storage, thus water can pool in a depression until it is able to either build up enough head to overcome the topography, infiltrate into the ground, or evaporate into the air.

GSSHA solves the diffusive wave equation using two-step explicit finite volume schemes to route water for both 1-D channels and 2-D overland flow, where flows are computed based on heads, and volumes are updated based on the computed flows. Compared with more sophisticated implicit finite difference and finite element schemes, the algorithm used in *GSSHA* is simple. The friction slope between one grid cell and its neighbors is calculated as the difference in water surface elevations divided by the grid size. Compared with the kinematic wave approach, this diffusive wave approach allows *GSSHA* to route water through pits or depressions, and regions of adverse slope. The Manning formula is used to relate flow depth to discharge. Use of the Manning formula implies that the flow is both turbulent and that the roughness is not dependent on flow depth. Neither of these assumptions may be valid on the overland flow plane. While being simple, the method is powerful because it allows calculations to proceed when only portions of the stream network or watershed are flowing. This is an important attribute as rainfall may occur on only a portion of the watershed. The channel routing scheme was developed to allow water to remain in the channel after channel routing ends, and for water to be present in the channel when channel routing begins. Because groundwater may discharge to the stream at anytime, channel routing is initiated anytime a minimum amount of water is in the channel network. If the channel routing scheme indicates there is no flow in the channel, channel routing is halted during periods outside precipitation events. Fluxes between the stream and the groundwater are still computed and adjustments to the stream volumes are made without routing. If groundwater discharges to the stream, channel routing will resume, but at the groundwater time step, which is typically larger than the channel routing time step.

In order to estimate overland erosion, *GSSHA* employs an equation based on the work of Kilinc and Richardson (1973). Their investigation resulted in a sediment transport equation of uniform flow sheet and rill erosion on bare sandy soil. Julien (1995) modified the original Kilinc-Richardson equation to expand the applicability of the equation to non-uniform flow with consideration of soil and land-use specific factors (i.e., USLE factors, K, C, and P). The K, C, and P factors are empirical coefficients with the same conceptual meaning as those used in the Universal Soil Loss Equation. The surface of each grid cell is either eroded or aggraded depending upon the quantity of sediment in suspension and the potential sediment transport rates. This determination is made for three grain sizes, sand, silt, and clay. Conservation of mass of sediment determines what amount of sediment entering each grid cell stays in suspension, and what amount is deposited. The sediment transport capacity is satisfied by sediments already in suspension, previously deposited sediments, and then sediments in the parent material, respectively. If sediments in suspension are unable to satisfy the potential transport rate, the previously deposited sediment is used to satisfy the demand. If there is insufficient previous deposition, then the surface is eroded to meet the demand. If the potential sediment transport rates calculated are insufficient to transport the sediment already in suspension within a grid cell, sediment is deposited on the surface, Johnson (1997).

The present version of *GSSHA* employs the unit stream power method of Yang's (1973) for routing sand-size total-load in stream channels. Unit stream power is defined as the product of the average flow velocity, U, and the channel slope S_o. The rate of work done per unit weight of water in transporting sediment is assumed directly related to the rate of work available per unit weight of water. Thus, the total sediment concentration or total bed-material load must be directly related to the unit stream power. In the channels, silt and clay size particles are assumed to be in suspension, and are transported as wash load. This treatment implies that the flow is turbulent, and the travel time to the outlet of the catchment is short compared to the settling time, such that particles do not settle in the channel network. This assumption, combined with no bank erosion, results in the channels being neither a source nor sink of fines. Routing of suspended fines is a natural extension of the explicit diffusive-wave channel routing method. Suspended fine sediments are routed as concentrations. The concentration changes as a function of gradients in both concentration and velocity.

SWWRP-NSM

Currently SWWRP-NSMv1.0 allows multiple Nitrogen and Phosphorus species in dissolved, adsorbed, and solid form to be modeled in the overland water column as well as the channel water column.

Overland Nutrient Processes

The overland fate processes, in SWWRP-NSM, were taken from the SWAT formulations. The nitrogen process descriptions, Figure 1, include: 1) denitrification; 2) nitrification; 3) hydrolysis; and 4) volatilization. The phosphorus process descriptions, Figure 2, include: 1) desorption/mineralization; 2) adsorption/immobilization; and 3) volatilization.

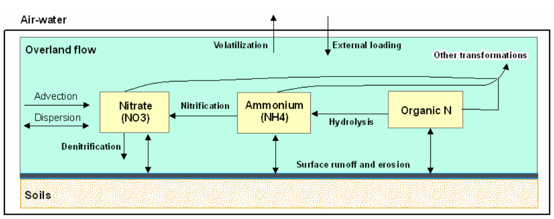

Figure 1 - Overland Nitrogen Processes

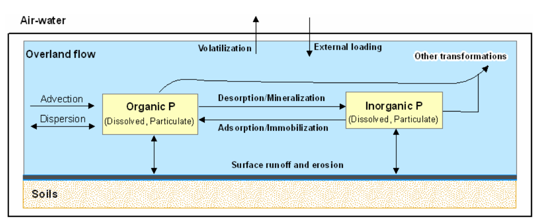

Figure 2 - Overland Phosphorus Processes

Channel Nutrient Processes

The channel fate processes, Figure 3, were initially taken from the QUAL2E formulations however, further enhancements are being taken from CE-QUAL-RIV1. In addition, a review is being done of the CE-QUAL-ICM and CE-QUAL-W2 kinetics in order to make sure that SWWRP-NSM is providing the proper nutrient species and phases in order to facilitate the linkage of nutrient runoff from the watersheds into the receiving waterbodies.

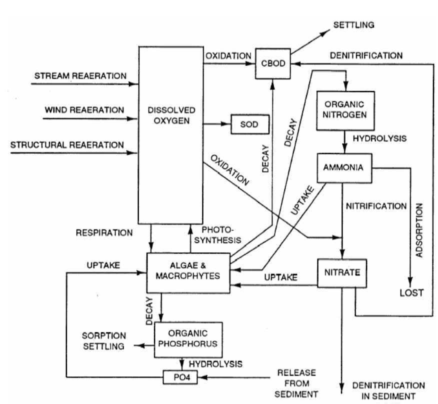

Figure 3 - Channel Nutrient Processes

Future Soil Nutrient Processes

Work in on-going to develop a soil module capable of performing the necessary carbon, nitrogen, and phosphorus kinetics. Schematics of the carbon, nitrogen, and phosphorus cycles can be seen in Figures 4 to 7. In developing the soil module, a review of various agency models (i.e., SWAT, AnnAGNPS, RZWQM, etc.) is being done in order to represent the necessary processes at the watershed scale. In addition, further research is being done at the Eau Galle Aquatic Ecology Laboratory (EGAEL) in an attempt to better understand and describe the fate processes related to Phosphorus. As new process descriptions are developed, the modular design of SWWRP-NSM will facilitate their inclusion into the *GSSHA* modeling system in addition to other modeling systems such as HEC-HMS, ADH, etc.

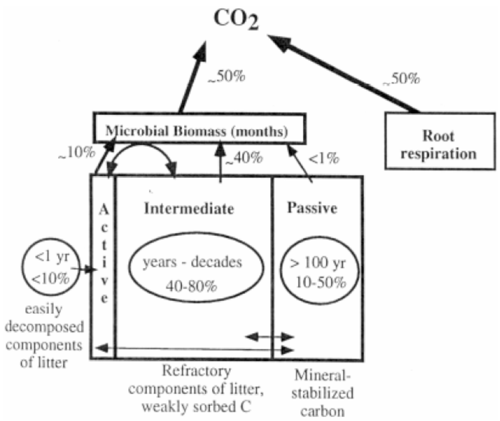

Figure 4 - Carbon Cycle

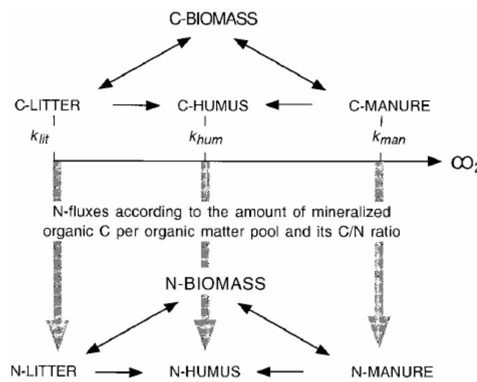

Figure 5 - Carbon Biomass Cycle

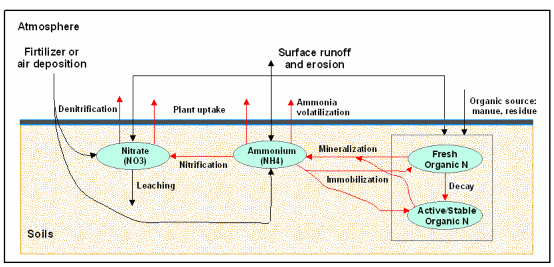

Figure 6 - Soil Nitrogen Cycle

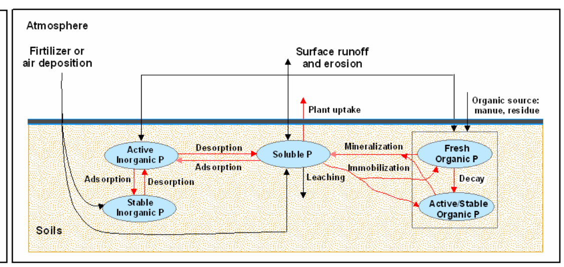

Figure 7 - Soil Phosphorus Cycle

Future Plant Growth Processes

Current development efforts are centered around linking the EDYS model with the *GSSHA* model. The Ecological DYnamics Simulation (EDYS) model, Figure 8, is a PC-based, mechanistic, spatially-explicit, and temporally-dynamic simulation model developed by Terry McLendon, Michael Childress, and Cade Coldren (Childress and McLendon 1999, Childress *et al*. 1999a, 1999b). EDYS simulates changes in soil, water, plant, animal, and landscape components resulting from natural and anthropogenic ecological stressors (McLendon *et al*. 1999, Childress *et al*. 2002). EDYS has been applied to over 40 ecological communities, including deserts, forests, grasslands, shrublands, wetlands, salt marshes, woodlands, and highly disturbed areas. Application locations include Arizona, California, Colorado, Maine, Montana, Nevada, New Mexico, Texas, Utah, Washington, Wyoming, Australia, and Indonesia.

EDYS consists of Climate, Soil, Hydrologic, Plant, Animal, Stressor, Spatial, Landscape, Management, and Simulation Control modules.

- In the Climatic Module, precipitation and wind inputs can be historical, stochastically generated, or a combination of both.
- The Soil Module is divided into layers (horizons, subhorizons, or artificial layers), the number, depth, and physical and chemical characteristics of which are site-specific for each application.
- The Hydrologic Module provides for infiltration and water movement through the soil profile, surface movement of water, surface erosion, sediment transport, subsurface movement of water, and changes in water quality.
- The Plant Module includes above- and below-ground components for each species included in each user-defined suite. Plant growth is dynamic in relation to plant components (roots, trunk, stems, leaves, seeds, and standing dead), season, resource requirements (water, nutrients, sunlight), and stressors (e.g., herbivory, competition, fire, trampling, chemical contaminants).
- The Animal Module consists of basic population parameters and diet attributes (preferences, utilization potential, competitive success) for each species (e.g., insects, rodent, native ungulates, livestock).
- The Stressor Module includes drought, nutrient availability, fire, herbivory, contaminants, shading, and competition for soil moisture and nutrients.
- The Spatial Module allows growth of individual plants (e.g., trees) and distribution patterns (e.g., colonies, fire patterns, soil heterogeneity) to be explicitly represented in the simulations.
- The Landscape Module allows for multi-scale simulations: plots (typically 1-100 m^2), communities (typically 1-100 hectares), and landscapes (1 km^2 and larger).
- The Management Module allows simulation of a variety of management activities, including agriculture, revegetation, weed and brush control, construction, reclamation, recreation, and military training.
- The Simulation Control Module coordinates the timing of simulation of ecological processes, allowing time steps for different processes to vary from daily (e.g., precipitation events, plant water demand, fire, herbivory), to monthly (e.g., species composition), to annual and longer (e.g., climatic cycles).

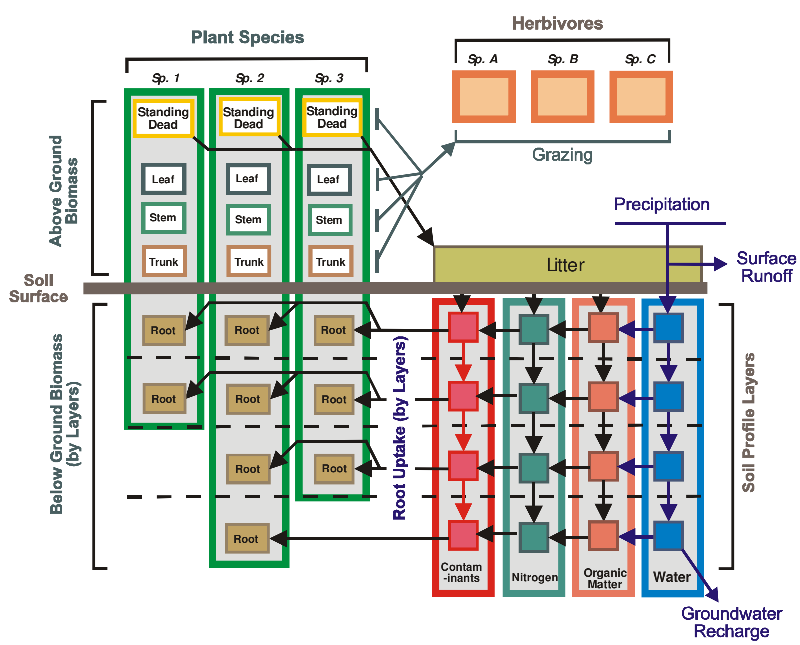

Figure 8 - EDYS Schematic

MODEL APPLICATION

The study area selected for testing the nutrient kinetics and transport modules is the Eight Mile Creek Watershed located within the Eau Galle Watershed in Wisconsin, Figure 9.

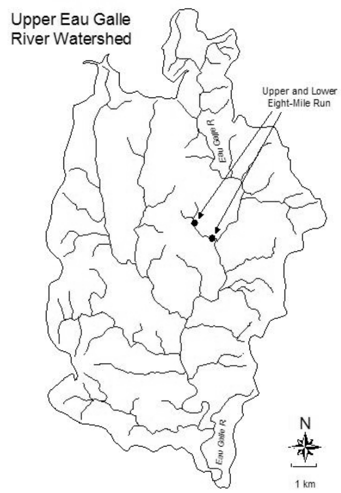

Figure 9 - Site Map for Eight Mile Creek Watershed

The Eight-Mile Creek Watershed is approximately 2.3 square kilometers with a maximum elevation of 385 meters NGVD and a minimum elevation of 340 meters NGVD, Figure 10. The watershed is rural in nature with landuse consisting of four major types: 1) Wooded; 2) Pasture; 3) Row Crop (Corn); and 4) Dairy, Figure 11. The soil texture is assumed to be uniformly distributed throughout the watershed and is classified as silt loam.

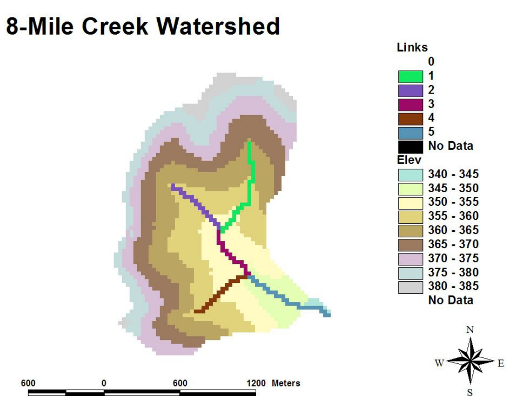

Figure 10 - DEM and Channels (meters)

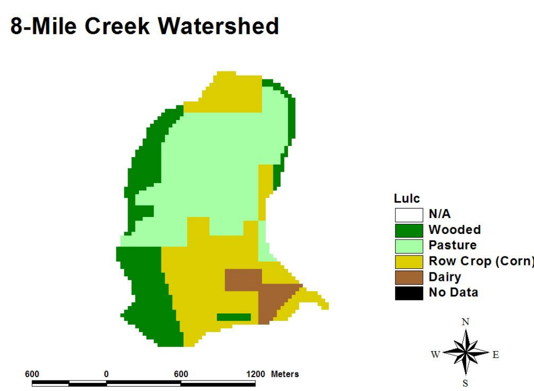

Figure 11 - Landuse

Detailed results of this case study will be presented at the conference.

CONCLUSIONS

The initial development effort focused on the process descriptions found within the SWAT modeling system. It is recognized that the SWWRP-NSM developers need to incorporate process descriptions from a wide variety of modeling systems in addition to working with engineers and scientist to develop better process descriptions. With this in mind, future efforts will be coordinated with engineers and scientists from other federal agencies in addition to private companies and universities. The modular framework, of SWWRP-NSM, lends itself to efficiently incorporating the latest descriptions in addition to linking with a number of hydraulic and hydrologic modeling systems. By using this framework, as SWWRP-NSM is modified, the various H&H modeling systems can be upgraded faster and more efficiently. In addition, by using a common water quality framework, the linkage of various H&H modeling systems can be better accommodated. This will result in a true system wide capability for modeling nutrients from the headwaters to the receiving waterbodies.

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